What is claimed is:

1. A phase and frequency tracking apparatus for multi-carrier systems, comprising:

an mth-order tracking loop for computing a phase tracking value, a normalized frequency tracking value and a normalized acceleration tracking value for a current symbol based on a phase estimate of said current symbol and a plurality of loop parameters;

a frequency predictor for calculating as output a feedback compensation frequency for a next symbol based on an equivalent feedback delay, said normalized frequency tracking value and said normalized acceleration tracking value of said current symbol; and

a pre-DFT synchronizer for compensating the phase and frequency of a received signal in a time domain using said feedback compensation frequency before taking an N-point Discrete Fourier Transform (DFT).

2. The apparatus as recited in claim 1 wherein said mth-order tracking loop is a third-order tracking loop modeled with a set of recursive equations, as follows:

$$\begin{aligned} \phi_{T,i} &= \phi_{P,i} + \mu_{\phi,i}\phi_{\varepsilon,i} \\ \Omega_{T,i} &= \Omega_{P,i} + \mu_{f,i}\phi_{\varepsilon,i} \\ a_{T,i} &= a_{T,i-1} + \mu_{a,i}\phi_{\varepsilon,i} \end{aligned}$$

and

$$\phi_{P,i+1} = \phi_{T,i} + \Omega_{T,i}$$
$$\Omega_{P,i+1} = \Omega_{T,i} + a_{T,i}$$

where

subscript i denotes a symbol index,

$\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$ respectively denote said phase, said normalized frequency and said normalized acceleration tracking values of symbol i,

$\mu_{\phi,i}$, $\mu_{f,i}$ and $\mu_{a,i}$ respectively denote said loop parameters of the ith symbol for $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$,

$\phi_{P,i}$ and $\Omega_{P,i}$ respectively denote a phase prediction value and a normalized frequency prediction value of the ith symbol,

$\phi_{P,i+1}$ and $\Omega_{P,i+1}$ are said phase and said normalized frequency prediction values of symbol $i+1$,

$a_{T,i-1}$ is said normalized acceleration tracking value of symbol $i-1$,

and $\phi_{\varepsilon,i}$, a phase prediction error of the ith symbol, is given by:

$$\phi_{\varepsilon,i} = \phi_{E,i} - \phi_{P,i}$$

where $\phi_{E,i}$ denotes said phase estimate of the ith symbol.

3. The apparatus as recited in claim 2 wherein initial values of said phase, said normalized frequency and said normalized acceleration tracking values, $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$, are set to zero, for $i=-1$; said loop parameters $\mu_{f,i}$ and $\mu_{a,i}$ are equal to zero, for $i=0$.

4. The apparatus as recited in claim 2 wherein said feedback compensation frequency is calculated for said next symbol from:

$$\Omega_{C,i+1} = \Omega_{T,i} + D_f a_{T,i}$$

where D_f is a numerical representation of said equivalent feedback delay and $\Omega_{C,i+1}$ is said feedback compensation frequency of symbol $i+1$.

5. The apparatus as recited in claim 1 wherein said pre-DFT synchronizer receives said feedback compensation frequency of the ith symbol, $\Omega_{C,i}$, to compensate the frequency of said received signal and de-rotate the phase of said received signal in the time domain before taking the N-point DFT, by:

$$\tilde{r}_i[n] = r_i[n]\ e^{j\Omega_{C,i}\frac{(N-1)-2n}{2N'}}, \quad 0 \le n \le N-1$$

where n denotes a sample index, $r_i[n]$ denotes said received signal of sample n of symbol i, and N' is the number of samples in a symbol interval.

6. A phase and frequency tracking apparatus for multi-carrier systems, comprising:

an mth-order tracking loop for computing a phase tracking value, a normalized frequency tracking value and a normalized acceleration tracking value for a current symbol based on a phase estimate of said current symbol and a plurality of loop parameters, wherein said phase tracking value is employed to compensate for an effect of phase drift; and

a frequency predictor for calculating as output a feedback compensation frequency for a next symbol based on an equivalent feedback delay, said normalized frequency tracking value and said

normalized acceleration tracking value of said current symbol, whereby pre-DFT synchronization can be accomplished using said feedback compensation frequency.

7. The apparatus as recited in claim 6 wherein said phase estimate of said current symbol, $\phi_{E,i}$, is computed from the following function:

$$\phi_{E,i} = \text{angle}\left(\sum_{m=1}^{N_{SP}} R'_{i,p_m}\left(H_{p_m} X_{i,p_m}\right)^*\right)$$

where

superscript * denotes complex conjugation,

subscript i denotes a symbol index,

N_{SP} is the number of the pilot subcarriers,

subscript p_m denotes a pilot subcarrier index, *for* $m = 1, \ldots, N_{SP}$,

H_{p_m} denotes said channel response of pilot subcarrier p_m,

X_{i,p_m} denotes said transmitted data on pilot subcarrier p_m of symbol i,

R'_{i,p_m} denotes said timing compensated version of the ith symbol on pilot subcarrier location p_m, and

$\phi_{E,i}$ represents said phase estimate of the ith symbol.

8. The apparatus as recited in claim 6 wherein said mth-order tracking loop is a third-order tracking loop modeled with a set of recursive equations, as follows:

$$\begin{aligned}\phi_{T,i} &= \phi_{P,i} + \mu_{\phi,i}\phi_{\varepsilon,i}\\ \Omega_{T,i} &= \Omega_{P,i} + \mu_{f,i}\phi_{\varepsilon,i}\\ a_{T,i} &= a_{T,i-1} + \mu_{a,i}\phi_{\varepsilon,i}\end{aligned}$$

and

$$\phi_{P,i+1} = \phi_{T,i} + \Omega_{T,i}$$
$$\Omega_{P,i+1} = \Omega_{T,i} + a_{T,i}$$

where

subscript i denotes a symbol index,

$\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$ respectively denote said phase, said normalized frequency and said normalized acceleration tracking values of symbol i,

$\mu_{\phi,i}$, $\mu_{f,i}$ and $\mu_{a,i}$ respectively denote said loop parameters of the ith symbol for $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$,

$\phi_{P,i}$ and $\Omega_{P,i}$ respectively denote a phase prediction value and a normalized frequency prediction value of the ith symbol,

$\phi_{P,i+1}$ and $\Omega_{P,i+1}$ are said phase and said normalized frequency prediction values of symbol $i+1$,

$a_{T,i-1}$ is said normalized acceleration tracking value of symbol $i-1$,

and $\phi_{\varepsilon,i}$, a phase prediction error of the ith symbol, is given by:

$$\phi_{\varepsilon,i} = \phi_{E,i} - \phi_{P,i}$$

where $\phi_{E,i}$ denotes said phase estimate of the ith symbol.

9. The apparatus as recited in claim 8 wherein initial values of said phase, said normalized frequency and said normalized acceleration tracking values, $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$, are set to zero, for $i=-1$; said loop parameters $\mu_{f,i}$ and $\mu_{a,i}$ are equal to zero, for $i=0$.

10. The apparatus as recited in claim 8 wherein said feedback compensation frequency is calculated for said next symbol from:

$$\Omega_{C,i+1} = \Omega_{T,i} + D_f a_{T,i}$$

where D_f is a numerical representation of said equivalent feedback delay and $\Omega_{C,i+1}$ is said feedback compensation frequency of symbol $i+1$.

11. The apparatus as recited in claim 6 wherein said feedback compensation frequency of the ith symbol, $\Omega_{C,i}$, is provided as feedback to de-rotate a received signal prior to taking the N-point DFT, by:

$$\tilde{r}_i[n] = r_i[n]\, e^{j\Omega_{C,i}\frac{(N-1)-2n}{2N'}}, \quad 0 \le n \le N-1$$

where n denotes a sample index, $r_i[n]$ denotes said received signal of sample n of symbol i, and N' is the number of samples in a symbol interval.

12. A phase and frequency drift compensation apparatus for multi-carrier systems, comprising:

a timing offset compensator for receiving a current symbol in a frequency domain after taking an N-point Discrete Fourier Transform (DFT) and compensating for a timing offset in said current symbol;

a phase estimator for taking a timing compensated version of said current symbol on pilot subcarrier locations and computing a phase estimate for said current symbol based on a function of a channel response of each pilot subcarrier, transmitted data on each pilot subcarrier, and said timing compensated version of said current symbol on said pilot subcarrier locations;

an mth-order tracking loop for computing a phase tracking value, a normalized frequency tracking value and a normalized acceleration tracking value for said current symbol based on said phase estimate of said current symbol and a plurality of loop parameters;

a frequency predictor for calculating as output a feedback compensation frequency for a next symbol based on an equivalent feedback delay, said normalized frequency tracking value and said normalized acceleration tracking value of said current symbol;

a pre-DFT synchronizer for compensating the phase and frequency of a received signal in a time domain using said feedback compensation frequency before taking the N-point DFT; and

a phase compensator for compensating said timing compensated version of said current symbol for an effect of phase drift with said phase tracking value of said current symbol.

13. The apparatus as recited in claim 12 wherein said mth-order tracking loop is a third-order tracking loop modeled with a set of recursive equations, as follows:

$$\begin{aligned}\phi_{T,i} &= \phi_{P,i} + \mu_{\phi,i}\phi_{\varepsilon,i}\\ \Omega_{T,i} &= \Omega_{P,i} + \mu_{f,i}\phi_{\varepsilon,i}\\ a_{T,i} &= a_{T,i-1} + \mu_{a,i}\phi_{\varepsilon,i}\end{aligned}$$

and

$$\begin{aligned}\phi_{P,i+1} &= \phi_{T,i} + \Omega_{T,i}\\ \Omega_{P,i+1} &= \Omega_{T,i} + a_{T,i}\end{aligned}$$

where

subscript i denotes a symbol index,

$\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$ respectively denote said phase, said normalized frequency and said normalized acceleration tracking values of symbol i,

$\mu_{\phi,i}$, $\mu_{f,i}$ and $\mu_{a,i}$ respectively denote said loop parameters of the ith symbol for $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$,

$\phi_{P,i}$ and $\Omega_{P,i}$ respectively denote a phase prediction value and a normalized frequency prediction value of the ith symbol,

$\phi_{P,i+1}$ and $\Omega_{P,i+1}$ are said phase and said normalized frequency prediction values of symbol $i+1$,

$a_{T,i-1}$ is said normalized acceleration tracking value of symbol $i-1$,

and $\phi_{\varepsilon,i}$, a phase prediction error of the ith symbol, is given by:

$$\phi_{\varepsilon,i} = \phi_{E,i} - \phi_{P,i}$$

where $\phi_{E,i}$ denotes said phase estimate of the ith symbol.

14. The apparatus as recited in claim 13 wherein initial values of said phase, said normalized frequency and said normalized acceleration tracking values, $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$, are set to zero, for $i=-1$; said loop parameters $\mu_{f,i}$ and $\mu_{a,i}$ are equal to zero, for $i=0$.

15. The apparatus as recited in claim 13 wherein said feedback compensation frequency is calculated for said next symbol from:

$$\Omega_{C,i+1} = \Omega_{T,i} + D_f a_{T,i}$$

where D_f is a numerical representation of said equivalent feedback delay and $\Omega_{C,i+1}$ is said feedback compensation frequency of symbol i+1.

16. The apparatus as recited in claim 12 wherein said pre-DFT synchronizer receives said feedback compensation frequency of the ith symbol, $\Omega_{C,i}$, to compensate the frequency of said received signal and de-rotate the phase of said received signal in the time domain before taking the N-point DFT, by:

$$\tilde{r}_i[n] = r_i[n]\ e^{j\Omega_{C,i}\frac{(N-1)-2n}{2N'}}\ ,\quad 0 \le n \le N-1$$

where n denotes a sample index, $r_i[n]$ denotes said received signal of sample n of symbol i, and N' is the number of samples in a symbol interval.

17. The apparatus as recited in claim 12 wherein said phase estimator computes said phase estimate of said current symbol, $\phi_{E,i}$, by means of the following function:

$$\phi_{E,i} = \text{angle}\left(\sum_{m=1}^{N_{SP}} R'_{i,p_m} \left(H_{p_m} X_{i,p_m}\right)^* \right)$$

where

superscript * denotes complex conjugation,

subscript i denotes a symbol index,

N_{SP} is the number of the pilot subcarriers,

subscript p_m denotes a pilot subcarrier index, *for* $m = 1, \ldots, N_{SP}$,

H_{p_m} denotes said channel response of pilot subcarrier p_m ,

X_{i,p_m} denotes said transmitted data on pilot subcarrier p_m of symbol i,

R'_{i,p_m} denotes said timing compensated version of the ith symbol on pilot subcarrier location p_m, and

$\phi_{E,i}$ represents said phase estimate of the ith symbol.

18. A phase and frequency tracking apparatus for multi-carrier systems, comprising:

a pre-DFT synchronizer for compensating the phase and frequency of a received signal in a time domain using a feedback compensation frequency before taking an N-point Discrete Fourier Transform (DFT).

19. The apparatus as recited in claim 18 wherein said pre-DFT synchronizer receives said feedback compensation frequency of the ith symbol, $\Omega_{C,i}$, to compensate the frequency of said received signal and de-rotate the phase of said received signal in the time domain before taking the N-point DFT, by:

$$\tilde{r}_i[n] = r_i[n]\, e^{j\Omega_{C,i}\frac{(N-1)-2n}{2N'}}, \quad 0 \le n \le N-1$$

where n denotes a sample index, $r_i[n]$ denotes said received signal of sample n of symbol i, and N' is the number of samples in a symbol interval.